UCRL-92206
PREPRINT

HIGH $I\lambda_{\mu}^{2}$ UNDERDENSE PLASMA HEATING

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This paper was prepared for submittal to Physics of Fluids.

February 14, 1985

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DISCLAIMER

High $I\lambda_\mu^2$ underdense plasma heating

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We use a one dimensional relativistic, electromagnetic, kinetic computer simulation to measure the heated electron temperatures and absorption of laser light at $I\lambda_\mu^2$ approaching $10^{18}\mathrm{W}\cdot\mu\mathrm{m}^2/\mathrm{cm}^2$. We find very rapid absorption to 0.1 to 1Mev temperatures by a mechanism that is a mixture of forward and back Raman scattering. The higher intensities lead to preferential absorption by Raman forward scattering and hence higher temperatures. We have evidence that the scattered light (both up and down shifted) is also strongly absorbed.

PACS: 52.50.Jm, 52.25.Ps, 52.40.Db, 52.35.Py

As $I\lambda_\mu^2$ approaches 10^{18} (as can easily occur with high power CO_2 lasers), the oscillatory velocity of electrons accelerated by the transverse electric field of the laser light wave approaches the speed of light. Here I is the laser intensity in W/cm^2 and λ_μ is the laser wavelength in microns. At these intensities, the spatial growth e-folding distance of Raman forward scattering[1] becomes less than a wavelength of light. Recent experiments and 2-D simulations[2] have found large absorption(~80%) into very high electron temperatures (approching 1 Mev) which this paper explains in terms of forward Raman scattering.

Stimulated Raman scattering(SRS)[1-11] (back, side and forward) in laser produced plasmas can generate high-energy electrons, which can reduce the energy gain of laser fusion targets. SRS is the parametric decay of an incident photon into a scattered photon plus a longtitudinal electron plasma wave. The wave numbers, k, and frequencies, ω, obey the matching conditions characteristic of parametric processes: $k_0=\pm k_s+k_{epw}$ and $\omega_0=\omega_s+\omega_{epw}$, (the subscripts 0,s, and epw refer to the pump, scattered, and electron plasma wave, respectively and the $-$ of $\pm$ refers to backscatter). The growth rate for Raman back and forward scatter is

$$\gamma_0/\omega_0=[k_{epw}c/(4\omega_0)](v_{osc}/c)[(\omega_p/\omega_s)(\omega_p/\omega_{epw})]^{1/2}[1-(n/n_c)]^{-1/4}. \quad (1)$$

Here $v_{osc}/c=eE_0/(cm_e\omega_0)=8.55\times10^{-10}\lambda_\mu[I(W/cm^2)]^{1/2}$, where E_0 is the laser peak vacuum electric field, ω_p is the plasma frequency at density, n, and n_c is the density where the laser frequency, ω_0, = ω_p. The spatial growth rate can be approximated by $k_i=\gamma_0/(v_{gs}v_{gepw})^{1/2}$ where $v_{gs}=c(1-\omega_p^2/\omega_s^2)^{1/2}$ and $v_{gepw}\simeq 3k_{epw}v_e^2/\omega_{epw}$. and are the group velocities of the scattered light and epw respectively.

This rapid heating can be seen in the simulation[1,3] phase space plot of Fig.1. The laser is incident from the left, and the long wavelength electron plasma wave is the Raman forward scatter wavelength and lags only $10\lambda_\mu$ behind the laser light wave. The noise for the forward scattered wave starts from the left and amplifies to the right. On the left part of the plot, one can see the short wavelength of the electron plasma wave due to Raman back scatter which is also superimposed on the long wavelength forward scatter at the right. The noise for Raman backscatter starts from the right and amplifies to the left. Possibly the reason why forward scattering is comparable to backscattering in spite of its slower spatial growth rate is that the electromagnetic turbulence from the laser–plasma interaction provides a large noise initialization.

The transmitted and reflected spectra are very broad as expected from the the large imaginary parts of the frequency due to both the growth rate and Landau damping[3]. Forward Raman spectra scatters into both up and down shifted light[3] since both modes satisfy ω and k matching whereas backscatter does not upshift since that is far from resonance.

The Manley–Rowe relations essentially state that the energy from the pump is partitioned into the scattered light wave and the electron plasma wave by ratios ω_s/ω_0 and ω_{epw}/ω_0 respectively. By examining the fraction of light into plasma heating and external scattering, one might initially conclude that Manley–Rowe is not obeyed; however, it is locally obeyed since the scattered light is so intense that it is subsequently absorbed. Even if the plasma density is over quarter critical for the scattered light, ($\omega_p^2/\omega_s^2>0.25$) the light can still be rapidly absorbed as shown by the points on Fig.2 for $n/n_c=0.5$.

Examination of the k plots of the electromagnetic light for these n/n_c=0.5 runs shows that internally, the light is upshifted to about $1.25\omega_0$ which is then rapidly absorbed. Note that the threshold for the absorption at n/n_c=0.5 is about at $I\lambda_\mu^2 \sim (1-3)\times10^{17} W\cdot\mu m^2/cm^2$. The mechanism is not clearly understood but may be a form of Compton scattering.[11]

The "temperatures" of Fig.2 were estimated from plots of the 2-D electron distribution functions as described in Ref.1. At lower intensities, we have observed two T_{hot}'s (ref.3), a lower one for backscatter and a higher one for forward scatter. However, in the extraordinarily turbulent regime described in this paper, there were generally not clear one or two temperature heated distributions. The "temperatures" of Fig.2 represents best fits of a single line to the electron distribution function. Of course, the temperatures increase non-linearly in time. The measurements of Fig.2 were taken at about the time the light wave traversed the system.

This fast heating is not due to a relativistic effect. Characteristic runs were repeated with the code not relativistic and the heating was even faster. Also the time and space steps were reduced to 64 per laser period and laser wavelength without significant change. To remove the oscillatory part of the heating, a wave packet was sent through the plasma and the heated electron temperature was measured after the electromagnetic wave had passed with similar results. Also the plasma length was doubled without substantial differences to the T_{hot}.

We note that the Los Alamos and UCLA groups[12] have recently published the results of two dimensional simulations with "S" polarization which show that Raman sidescatter also plays a large role in the high intensity parameter regime.

In conclusion, we have used a relativistic, electromagnetic, kinetic computer simulation to measure the heated electron "temperatures" and absorption of laser light at $I\lambda_{\mu}^{2}$ approaching $10^{18} W \cdot m^2/cm^2$. We find very rapid absorption to "temperatures" ~0.1 to 1 Mev by a mechanism that is a mixture of forward and backward Raman scattering. We have presented evidence thaa the scattered light (both up and down shifted) is also strongly absorbed. The higher intensities lead to preferential absorption by Raman forward scattering and hence higher "temperatures."

Work performed under the auspices of the U.S.Department of Energy by the Lawrence Livermore National Laboratory under contract number W7405-ENG-48.

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Figure Captions

Fig. 1. Electron phase space where the laser enters from the left. The long and short wavelength oscillations are Raman forward and back scattering respectively.

Fig. 2. Heated electron "temperatures" vs $I\lambda_\mu^2$ and n/n_c.

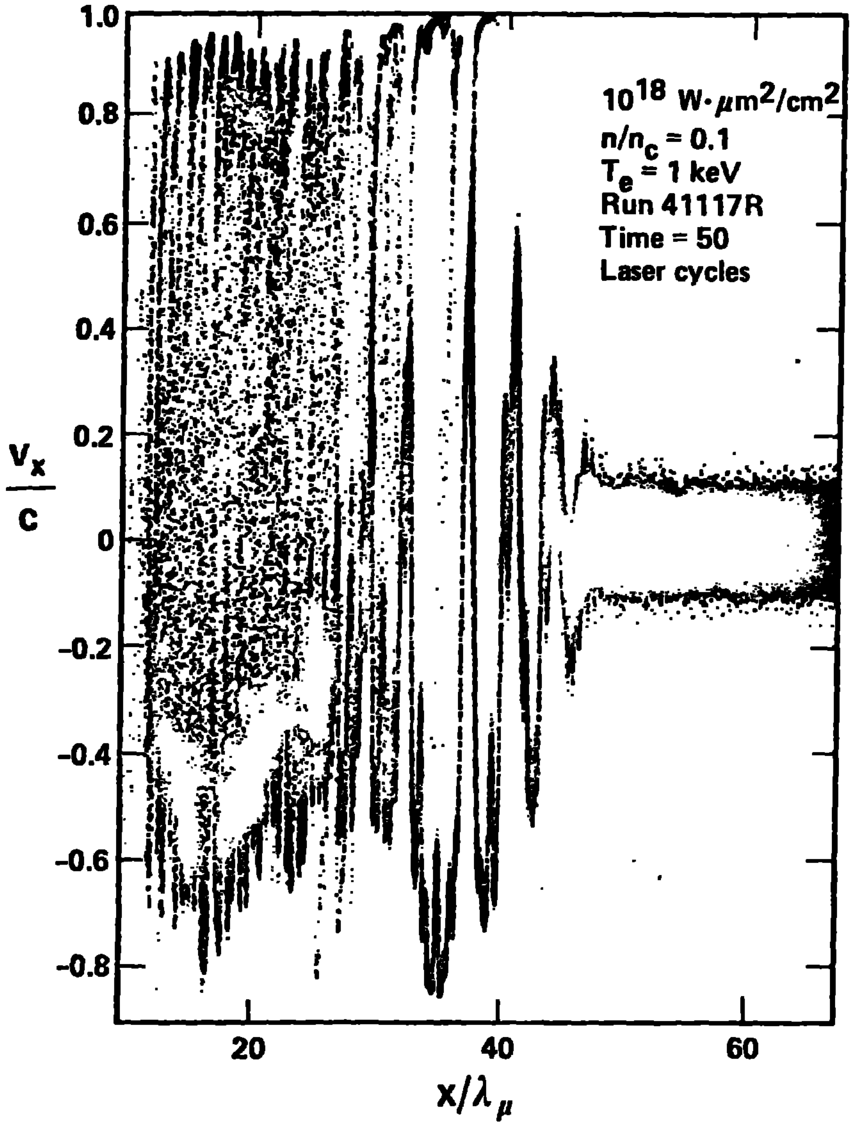

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Fig. 1

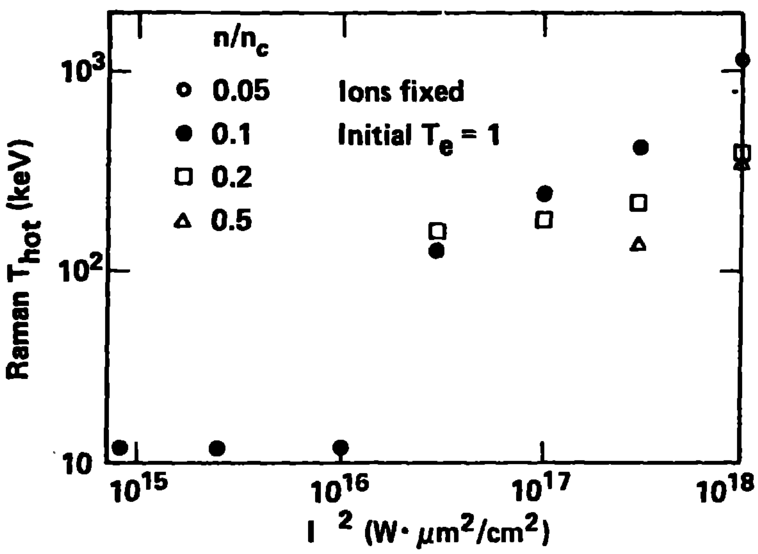

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Fig. 2